

# Recent Results on the Spatially Resolved Molecular Gas Star Formation Law from CARMA Survey Toward Infrared-bright Nearby Galaxies (STING)

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**Abstract.** Observational determinations of the functional relationship between star formation rate surface density and molecular gas surface density, commonly known as the star formation law, in galaxies require taking into account a number of factors. Extinction, contributions from non star-forming populations affect many measures of star formation, the treatment of the diffuse emission, and the statistical methodologies employed all have impacts on the precise relation between gas and star formation. Using CARMA STING data-set, a 3mm (CO J = 1-0) survey of nearby galaxies, we recently investigate the relationship at the sub-kpc level.

We find that precise observational constraint on the linear or non-linear functional form of the relationship requires an accurate estimate of the fraction of the diffuse emission. Our results show that the treatment of the diffuse emission has significant impact on the intrinsic scatter in the Schmidt-Kennicutt type star formation law. The scatter varies substantially with the choice of the star formation tracer used. For example, the mid-infrared non-linear 24  $\mu\text{m}$  star formation tracer shows the tightest correlation with the molecular gas content whereas (azimuthally averaged) extinction corrected H $\alpha$  as a tracer appears to be the noisiest. Measuring the relationship in the bright, high molecular gas surface density ( $\Sigma_{\text{H}_2} \sim 20 \text{ M}_\odot \text{ pc}^{-2}$ ) regions of the disks to minimize the contribution from diffuse extended emission and using 24  $\mu\text{m}$  emission as a tracer of star formation, we find an approximately linear relation between molecular gas and star formation rate surface density with a molecular gas depletion time  $\sim 2.30$  Gyr.

## 1. Introduction

Observational evidence suggest that stars form within molecular clouds. However, the processes responsible for converting gas into stars in various galactic environments are still poorly understood. Observations find that the star formation rate (SFR) and the gas content in galaxies are related by,  $\Sigma_{\text{SFR}} = A \Sigma_{\text{gas}}^N$ , where  $\Sigma_{\text{SFR}}$  and  $\Sigma_{\text{gas}}$  are the star formation rate surface density and the gas (atomic and molecular) surface density, respectively; and A is the normalization constant representing the efficiency of the processes ([1], [2], [3], [4], [5]). This relationship between gas and SFR surface densities is commonly referred to as the Schmidt-Kennicutt star formation (SF) law.

Spatially resolved SF law studies, whether it is a rigorous case study or a meticulous investigation of a sample, frequently reach dissimilar conclusions on the value of the exponent in the relation above when relating *molecular gas* to SFR (hereafter we express the exponent as  $N_{\text{mol}}$  to represent the molecular gas SF law). These studies provide a spread in the value of the power law index ranging from  $N_{\text{mol}} \sim 0.8 - 1.5$  ([6], [7], and references therein). Whether the local SF law is linear or non-linear has implications for the dominant SF mechanisms as well as for modeling efforts. Therefore, the extent in the value of the index within and among galaxies may be intrinsic and contain valuable astrophysical information, or be entirely attributable to the different choices of gas and SFR tracers, methodologies for internal extinction correction, differences in the CO-to-H<sub>2</sub> conversion, or the range of spatial scales probed.

To explore the impact of various methodological aspects related to the local SF law we recently make two comprehensive analyses of the SF law using high resolution ( $3'' - 5''$ ) STING<sup>1</sup> CO  $J = 1 - 0$  data procured from Combined Array for Research in Millimeter Astronomy (CARMA) interferometer observations. Our results are presented in [6] and [7]. Rahman *et al* 2011 [6] is a pilot project which centers on 1) the use of different SFR tracers and the scatter associated with those tracers, 2) the role of the diffuse emission (DE), a component of the integrated disk emission which is not necessarily related to the star-forming regions, and 3) the role of fitting methodologies and data sampling strategies in determining the functional form of the SF law. The insights obtain from this work leads us to further investigate the local SF at high (molecular gas) surface brightness regions for the STING sample galaxies [7]. In this report we underline the key results obtained from these studies.

## 2. Data

The STING sample is composed of 23 northern ( $\delta > -20^\circ$ ), moderately inclined ( $i < 75^\circ$ ) galaxies within 45 Mpc culled from the *IRAS* Revised Bright Galaxy Survey (RBGS; [8]). These galaxies have been carefully selected to have uniform coverage in stellar mass, SF activities, and morphological types. We use CO  $J = 1 - 0$  spectral cube to produce integrated CO intensity maps and then to construct molecular gas column density maps. To construct SFR tracer maps for the sample we use 24  $\mu\text{m}$  images from the Multi-band Imaging Photometers (MIPS; [9]) instrument on board the *Spitzer Space Telescope*. The calibrated mid-infrared images are obtained from the *Spitzer* Heritage Archive. The FUV and H $\alpha$  images of NGC 4254 are obtained from *GALEX* Nearby Galaxies Survey [10] and *Spitzer* Infrared Nearby Galaxies Survey [11]. The spatial resolution of our studies is limited by the point spread function of the 24  $\mu\text{m}$  map, which has a FWHM of  $6''$ . This angular resolution covers a range of physical scales in the sample,  $\sim 160$ -1250 pc, corresponding to physical distances  $\sim 5.5$ -43.1 Mpc. The higher resolution images were Gaussian-convolved to have the same image resolution and pixel sampling. Construction of various data products such as molecular gas surface density ( $\Sigma_{\text{H}_2}$ ) map, SFR surface density ( $\Sigma_{\text{SFR}}$ ) map and the associated error maps as well as data sampling and fitting strategies are described in detail in [6]. We use unsharp masking to model and remove the DE from the SFR tracer maps. However, unlike [6] which uses combined CO data (both single dish and interferometer), in this report we use only CARMA data to obtain molecular hydrogen. Since interferometric observation filters out extended emission, the CO data does not warrant the need to remove the DE.

## 3. Results and Analyses

### 3.1. NGC 4254: A Detailed Case Study

In Rahman *et al* 2011 [6] we exploit multi-wavelength data-set of NGC 4254 to conduct a thorough investigation of the impact of various methodological features in determining the

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functional form of the SF law. The available data facilitates a detailed analysis using four different SFR tracer maps including FUV and 24  $\mu\text{m}$ , extinction corrected  $\text{H}\alpha$ , observed  $\text{H}\alpha$  and 24  $\mu\text{m}$ , and only 24  $\mu\text{m}$ . We construct these maps following the prescriptions provided by [12], [13], and [14]. The variety of indicators is critical in appraising the robustness of the  $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$  relationship against the treatment of the DE.

While the details of different data samplings, various fitting considerations, and the technique to remove the DE can be found in [6], in Fig. 1 we underscore our results obtained from the pixel sampling and the OLS bisector fitting method only. In this figure a direct relation between the slope of the SF law and the magnitude of the DE subtracted in the pixel analysis is conspicuous: *subtraction of higher diffuse fraction corresponds to a steeper power-law index*. Compared to other sampling methods, this trend is *only* observed in the pixel analysis which contains the low surface brightness regions. Since the DE is proportionally more important in fainter regions, its subtraction increases scatter in the gas-SFR relation mostly at low surface densities. As a result, removing the DE steepens the SF law. It is also evident that the scatter in the SF law is substantially lower when no DE is subtracted from the total emission of the SFR tracers.

Among all SFR tracers mid-infrared 24  $\mu\text{m}$  displays the tightest correlation with the molecular gas ( $\sigma \sim 0.2$  dex from the OLS fitting). This is likely due to a combination of two effects: 1) the times scales for GMC dissipation by massive star formation and 24  $\mu\text{m}$  emission are essentially the same, and 2) by its nature, this SFR tracer does not need to be corrected by extinction. The extinction-corrected  $\Sigma_{\text{H}\alpha}$ , on the other hand, shows the largest scatter ( $\sigma \sim 0.5$  dex) of all tracers, irrespective of unsharp masking to remove the DE. This is due to the fact that the extinction correction is azimuthally averaged, and it does a poor job at correcting any one position although it yields the correct result in a statistical sense.

### 3.2. The Sample

Rahman *et al* 2012 [7] examines the  $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$  relation for 14 STING galaxies (including NGC 4254) by setting  $\Sigma_{\text{H}_2} > 20 \text{ M}_\odot \text{ pc}^{-2}$  to ensure that: 1) the signal-to-noise is good, 2) interferometric deconvolution issues are minimized, 3) the potential contribution by the DE is less problematic, and 4) we focus on regions dominated by molecular gas. The selection is based on secured CO  $J = 1 - 0$  detection, availability of data at other wavelengths, and the  $\Sigma_{\text{H}_2}$  threshold mentioned above. The molecular gas and star surface densities span a wide range,  $\Sigma_{\text{H}_2} \sim 20 - 1000 \text{ M}_\odot \text{ pc}^{-2}$  and  $\Sigma_{\text{SFR}} \sim 4 - 570 \text{ M}_\odot \text{ Gyr}^{-1} \text{ pc}^{-2}$ .

The left panel of Fig. 2 highlights spatially resolved pixel analysis for the STING sample. A simple correlation test shows that the points in this diagram are strongly correlated. We find a Pearson correlation coefficient  $r \sim 0.7$ . The OLS bisector method yields a power-law index  $N_{\text{mol}} \sim 1.1 \pm 0.1$  at this resolution, where the error is derived from bootstrapping. Despite the fact these measurements are coming from wide variety of galactic environments and galaxy properties, the ensemble of points yields an approximately linear SF law. The right panel of Fig. 2 shows molecular gas depletion time as a function of molecular gas surface density. It is clear from this diagram that the  $\text{H}_2$  depletion time has at most a very weak dependence on  $\Sigma_{\text{H}_2}$ . A small correlation coefficient ( $r \sim 0.2$ ) suggests that  $\tau_{\text{dep}}$  is mostly uniform across the disk.

The uniformity of  $\tau_{\text{dep}}$  over a wide range of  $\Sigma_{\text{H}_2}$  is most naturally explained as a consequence of the approximate constancy of the depletion time for molecular gas in GMCs. Indeed the observations of Local Group galaxies suggest that the properties GMCs are fairly uniform ([16], [17], [18]). In this scenario a linear SF law follows naturally, where the  $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$  relation arises from the number of GMCs filling the beam ([14], [15]). A linear molecular gas SF law is consistent with the scenario in which GMCs turn their masses into stars at an approximately constant rate, irrespective of their environmental parameters [19].

## 4. Summary and Conclusions

It is important to bear in mind that the choice of SFR tracers and spatial scales means that different studies effectively sample different time scales, thus the SF history of any particular galaxy potentially plays a vital role in determining the result of the measurement. It is also possible that these differences correspond to a spectrum of physical SF mechanisms present in a wide range of environments: in that case, the local SF law would not be universal. Using CARMA STING data-set we analyze the relationship between the SFR and molecular gas surface densities at the sub-kpc level to explore how the functional form of the SF law depends on the treatment of various data sampling. We also critically examine how different fitting techniques influence the outcome. In particular, we probe in-depth the contribution of the DE in various SFR tracers and its consequences on the spatially resolved SF law.

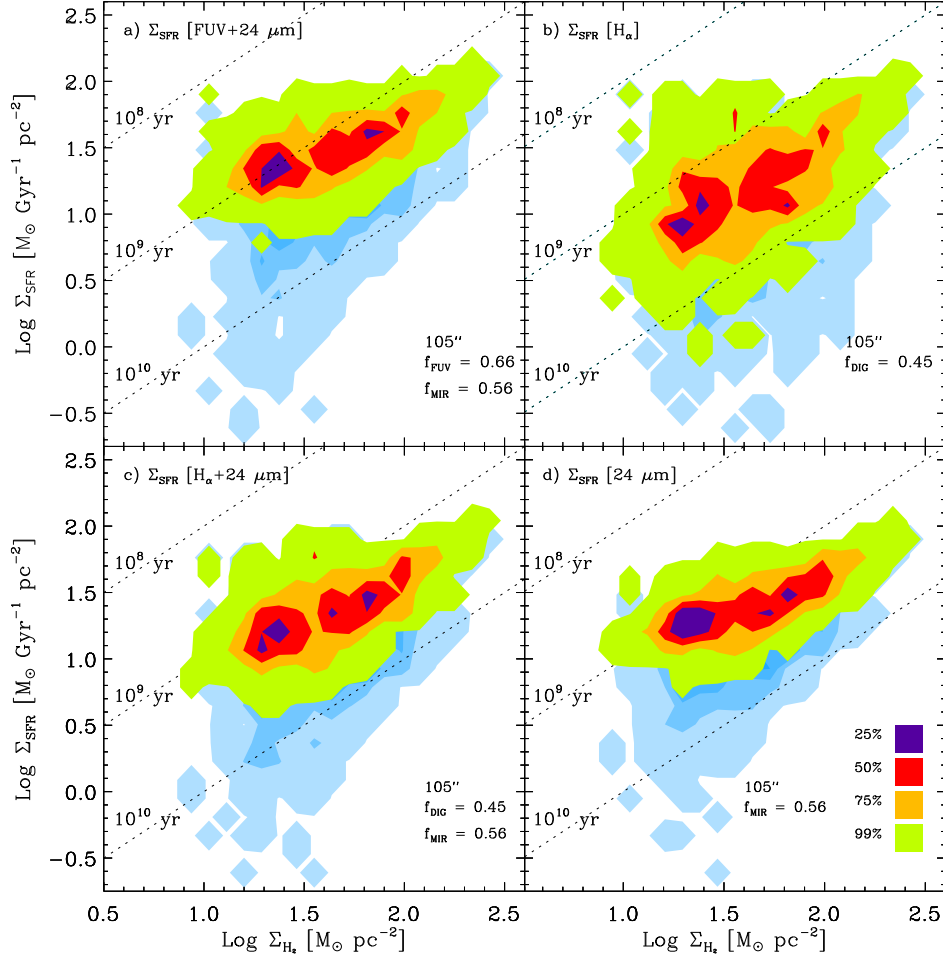
We find that a precise observational constraint on the linear or non-linear functional form of the relationship requires an accurate estimate of the fraction of the DE. Our results show that the treatment of the DE has notable impact on the intrinsic scatter in the canonical SF law. The scatter varies substantially with the choice of the SF tracer used. For example, the non-linear  $24\ \mu\text{m}$  star formation tracer shows the tightest correlation with the molecular gas content whereas (azimuthally averaged) extinction corrected  $\text{H}\alpha$  as a tracer appears to be the noisiest. Measuring the relationship in the bright, high molecular gas surface density ( $\Sigma_{\text{H}_2} \sim 20\ \text{M}_\odot\ \text{pc}^{-2}$ ) regions of the disks to minimize the contribution from diffuse extended emission and using  $24\ \mu\text{m}$  emission as a tracer of SF, we find an approximately linear relation between molecular gas and star formation rate surface density with a molecular gas depletion time  $\sim 2.30\ \text{Gyr}$ .

## Acknowledgments

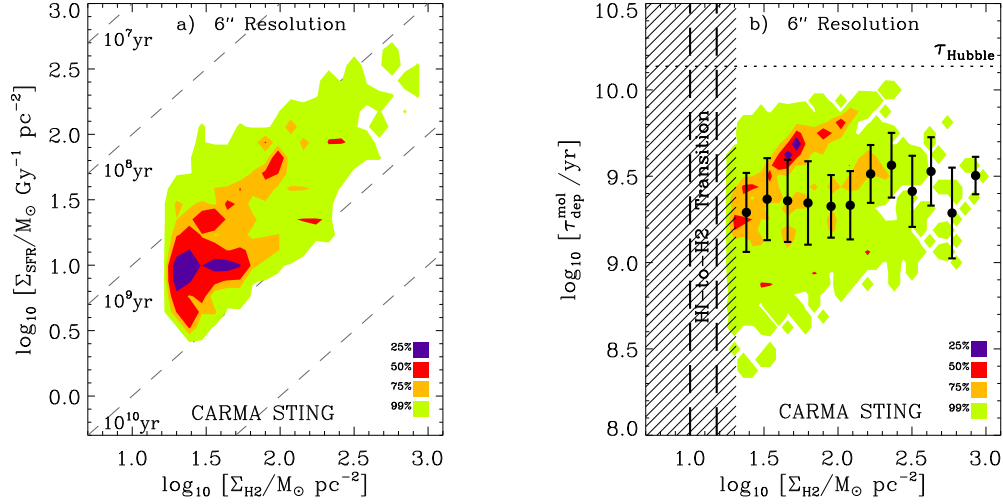
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**Figure 1.** Pixel analysis of the observed  $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$  relationship for NGC 4254 at  $6''$  resolution using four different SFR tracers (NGC 4254 a STING member galaxy). The figure shows the relationship when no DE is subtracted from the total emission of the SFR tracer (green-brown-red-blue contours) and at one particular filter scale of unsharp masking (blue contours) to highlight the significance of the subtraction of DE in the SF law. The contours are placed at 90%, 75%, 50%, and 25% of the maximum frequency. The diagonal dotted lines represent constant star formation efficiency ( $\epsilon$ ) where  $\epsilon \sim 100\%$ , 10%, and 1% correspond to gas depletion time scale,  $\tau_{\text{dep}} = 0.1, 1.0, \text{ and } 10$  Gyr. The  $1\sigma$  sensitivity limit of  $\Sigma_{\text{H}_2}$  map is  $\sim 5.3 M_{\odot} \text{ pc}^{-2}$  which is derived from CARMA CO  $J = 1 - 0$  observation. NGC 4254 is a normal star-forming spiral located at a kinematic distance of 16.6 Mpc. The  $6''$  angular scale corresponds to a physical length of  $\sim 480$  pc in the disk of the galaxy. It is apparent from the figure that the subtraction of the DE affects the low surface density regions and hence the functional form of the  $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$  relationship. It is also patent that  $\Sigma_{\text{H}\alpha}$  shows the largest scatter among all SFR tracers.



**Figure 2. Panel a:** Pixel analysis of the observed  $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$  relationship at 6'' resolution 14 CARMA STING galaxies (sample contains 23 galaxies). The panel shows a smoothed two-dimensional distribution where each point is weighted by the inverse of the total number of points of the contributing galaxy (all galaxies are equally important in the distribution, irrespective of the number of points they contribute). The contours of the smoothed distribution enclose 99%, 75%, 50% and 25% of the total. The diagonal dashed lines represent  $\tau_{\text{dep}}$  as in Fig. 1. **Panel b:** Molecular gas depletion time ( $\tau_{\text{dep}}$ ) versus  $\Sigma_{\text{H}_2}$  at 6'' resolution for the same galaxies shown in panel a. The horizontal dotted line represents the Hubble time, and the filled circles and associated error bars in black represent the median and  $1\sigma$  dispersion in  $\Sigma_{\text{H}_2}$  bins. The gray hatch illustrates the region where  $\Sigma_{\text{H}_2} < 20 M_{\odot} \text{pc}^{-2}$  which we remove from our analysis. Observational studies suggest that HI-to-H<sub>2</sub> phase transition occurs around  $\Sigma_{\text{H}_2} \sim 10$ - $15 M_{\odot} \text{pc}^{-2}$  and the nature of the (total) gas-SFR surface density relation changes dramatically around this range [13]. By sampling high  $\Sigma_{\text{H}_2}$  regions,  $\Sigma_{\text{H}_2} > 20 M_{\odot} \text{pc}^{-2}$ , therefore, we focus on the SF law in dominantly molecular region [7].